Project ID: ace154

Heavy-Duty Hybrid Diesel Engine with Front-End Accessory Drive-Integrated Energy Storage

Chad P. Koci

Caterpillar Inc.

June 22nd, 2022

2022 DOE Vehicle Technologies Office Annual Merit Review

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Overview

Timeline

- Start date: May 2019
- End date: June 2022
- ~95% Complete

Budget

- Total Funding: $7.46M
  - DOE share: $3.44M
  - Industrial share: $4.02M
- 2022: $0.59M

Barriers

- High-capability air handling equipment required for further engine downsizing
- Waste heat recovery and reduction in parasitic losses at reasonable costs
- Hybrid powertrain systems integration complexity and lack of modularity

Partners

- Project lead: Caterpillar
- SuperTurbo Technologies
- University of Texas at Austin

Relevance

- Objective
  - Research, develop, and demonstrate a heavy-duty hybrid diesel (H2D2) engine system for off-road applications
  - Performance Targets:
    - ***<u>17 (+/-2) % more fuel efficient than current Tier 4 diesel engine</u>***
    - Equivalent transient response vs. baseline diesel engine
    - Achieves Tier 4-Final Exhaust Emissions Levels

- Impact
  - Proposed improvements applied to off-road product range would save more than 25 million barrels of oil over 10 years
  - A crucial reduction in customer Total Cost of Ownership (TCO)

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Milestones

Date/Time	Description of Milestone or Go/No-Go	Status
May 2019	Project launch and kick-off meeting	**Complete**
December 2019	Hybrid Concept Finalized	**Complete**
January 2020	Baseline system CAD completed	**Complete**
April 2020	Baseline Thermofluid Simulation completed	**Complete**
June 2020 **Go/No-Go #1**	IF 1D system level simulation validates that the target total fuel consumption reduction AND Tier IV Final emissions AND the power system can be packaged in to target off-road machines; THEN proceed	**Complete – "Go"**
October 2020	Thermofluid, Structural & Dynamic Simulation Complete	**Complete**
December 2020	Variable FEAD, Turbo & TurboCompound, VVA System Design Complete	**Complete**
December 2020	HSFW, Beltdrive CVT, Aftertreatment Design, and Fuel System Design Complete	**Complete**
December 2020 **Go/No-Go #2**	IF the structural, dynamics simulations show that the target 12,000 hour durability can be achieved AND the subsystems demonstrate required performance on bench tests; THEN proceed	**Complete – "Go"**
December 2021	Engine Integration & Assembly Complete	**Complete**
May 2022	Hybrid Engine System Performance Validation Complete	On Track

Approach & Strategy

- Add hybrid power and energy aspects to enable:
  - Engine Downsizing
    - Transient load assist to *maintain machine productivity*
  - Energy Recovery
  - Start/Stop (or Anti-Idle)

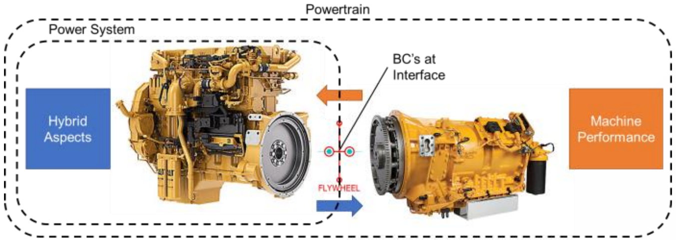
3 Key Off-road Applications

988K Large Wheel Loader

390F Hydraulic Excavator

745 Articulated Truck

- We will design a high-efficiency power system with a 13L concept engine - downsized from 18L – for use in off-road machine applications. The power system will have a hybrid front-end accessory drive (FEAD) that incorporates:
  - High-Speed Flywheel (HSFW)
  - Mechanical-drive Turbocharger (SuperTurbo)
  - Motor-Generator Unit (MGU)



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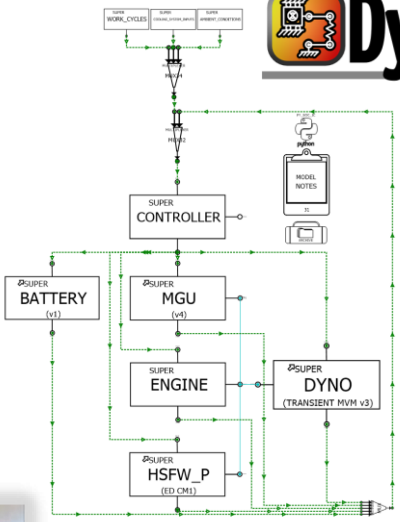
Approach & Strategy

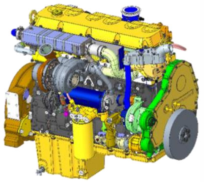
- Concept Design & Simulation
  - Systems-level modeling of hybrid power system concept
    - Define concept trade-offs & provide performance predictions
- Major Subsystem Analysis & Specification
  - 1D & 3D Thermofluid, Structural & Dynamic simulations
    - Address durability, performance, & modularity
- Phase 1 Concept Demonstrator Engine
  - Validate engine-only performance predictions
- Phase 2 Hybrid Engine System Validation
  - Complete power system validation in transient test cell
- Technoeconomic Analysis
  - Address cost barriers & provide TCO value assessment

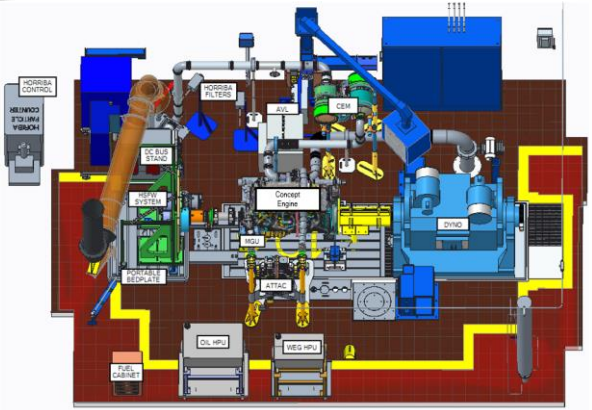
2020

2022

Dynasty







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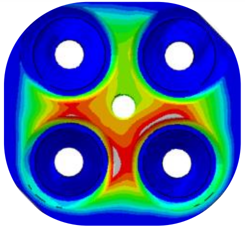
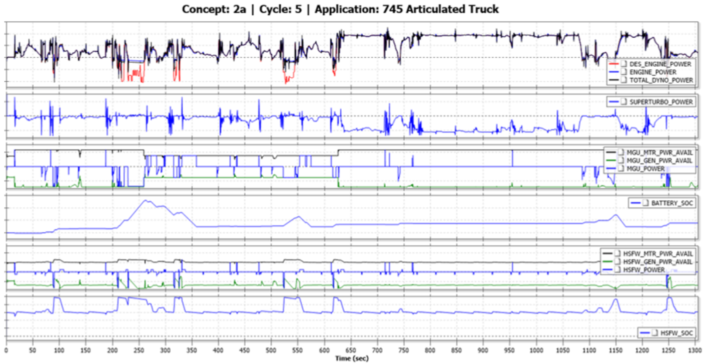
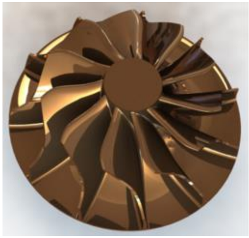
Technical Accomplishments & Progress

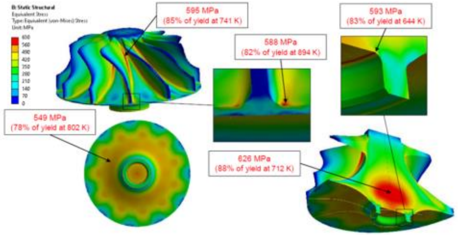


- Go / No-Go #1 – Passed
  - Extensive performance simulation
  - Phase 1 engine testing
  - Extensive load response simulation
  - Single cylinder testing of TBC's
  - Historical technology experience
  - Hybrid packaging assessment



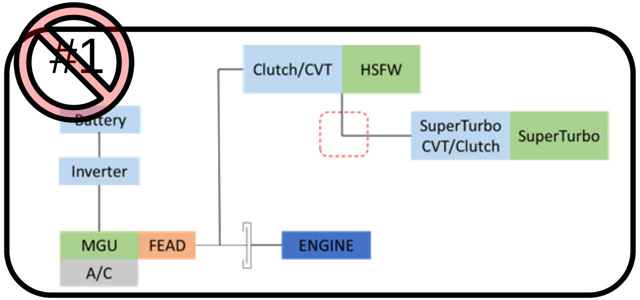
- Go / No-Go #2 – Passed
  - Core engine durability analyses
  - Valvetrain life simulation
  - SuperTurbo turbine durability sim.
  - SuperTurbo drive life simulation
  - Hybrid system durability analyses
  - HSFW fatigue & discharge analyses
  - Supplier component testing

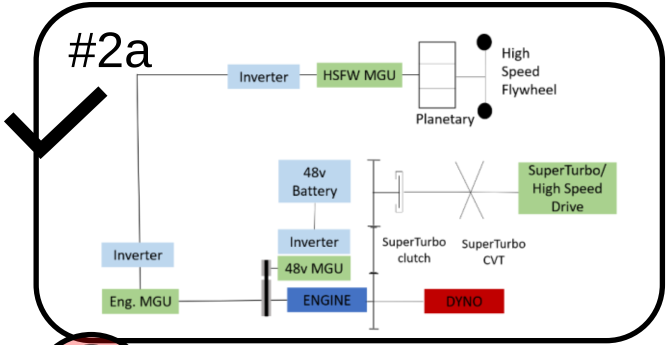


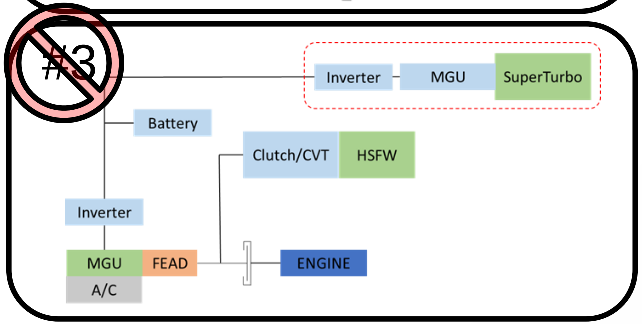


Technical Accomplishments & Progress

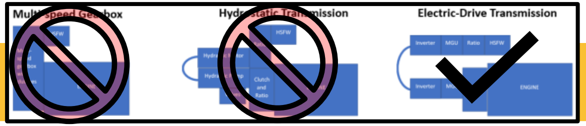
- All concepts simulated & analyzed – Main 3 concepts →
- #1 Eliminated (ST power through HSFW)
  - Speed range, packaging, compounding efficiency limitations
- #3 Eliminated (ST power through 48V battery+MGU)
  - Control & dev. complexity, non-electric ST option favored
- HSFW Belt-CVT Eliminated
  - Ratio response not fast enough → transient load response
  - Therefore, timeline immature for project
- **Final Concept "2a" selected** [1]
  - "a" denotes the electric-drive for the HSFW
  - Preferred for best transient response, complete HSFW-to-engine decoupling, and flexible packaging







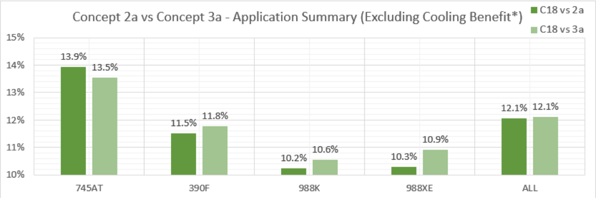
"a"

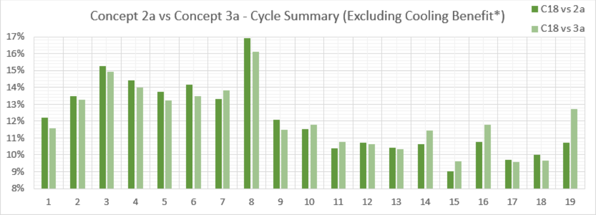


[1] Koci, C., Steffen, J., Kruiswyk, R., Guo, F. et al., "A Hybrid Heavy-Duty Diesel Power System for Off-Road Applications - Concept Definition," SAE Technical Paper 2021-01-0449, 2021, https://doi.org/10.4271/2021-01-0449.

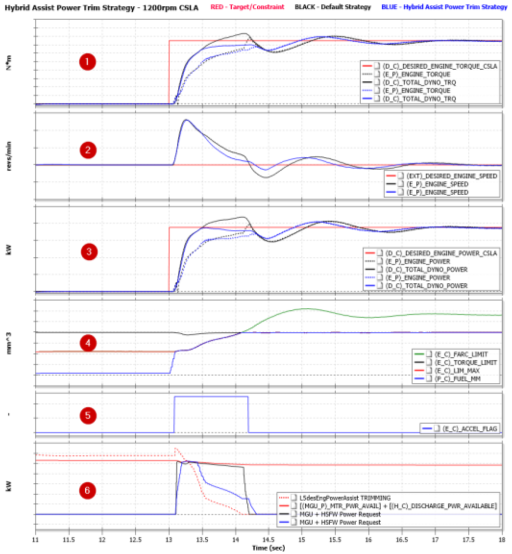
Technical Accomplishments & Progress

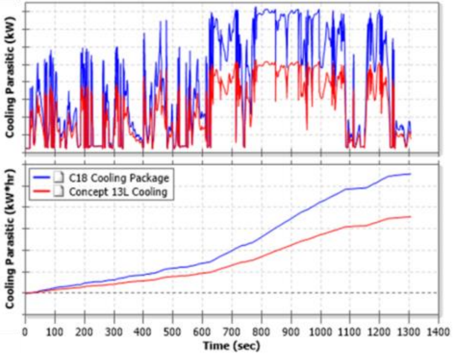
Dynasty

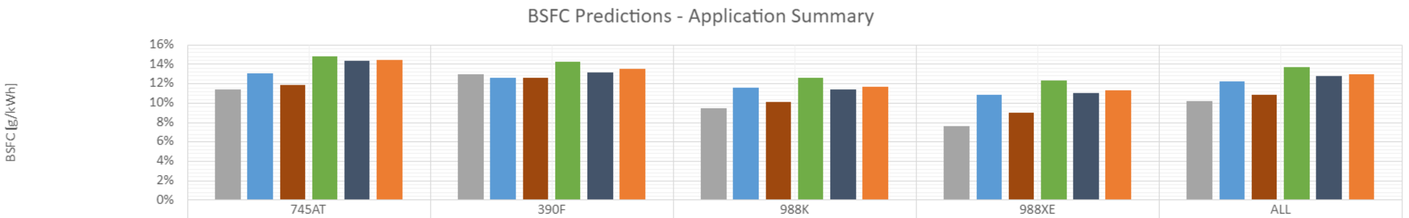




- System simulations underpin the concept (e.g., 2a vs. 3a concept)
- Ranges of benefit stem from application and cycle variation
- Transient hybrid strategy evolves with system maturity
- Cooling package benefits come from more efficient core engine







	745AT	390F	988K	988XE	ALL
13L BL v31 EGR FIX vs C18	11.38%	12.93%	9.40%	7.55%	10.13%
13L BL v32 vs C18	13.07%	12.55%	11.56%	10.84%	12.18%
13L BL v34 vs C18	11.79%	12.59%	10.04%	8.96%	10.78%
H2D2 HYBRID 2a v31 vs C18	14.81%	14.23%	12.59%	12.31%	13.67%
H2D2 HYBRID 2a v32 vs C18	14.34%	13.14%	11.33%	10.99%	12.78%
H2D2 HYBRID 2a v34 vs C18	14.43%	13.51%	11.61%	11.27%	12.98%

13L BL v31 EGR FIX vs C18 · 13L BL v32 vs C18 · 13L BL v34 vs C18 · H2D2 HYBRID 2a v31 vs C18 · H2D2 HYBRID 2a v32 vs C18 · H2D2 HYBRID 2a v34 vs C18

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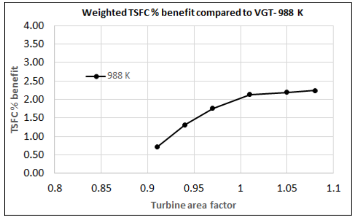
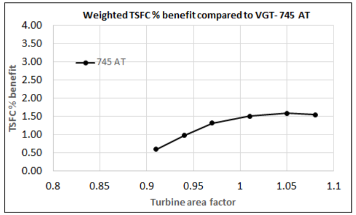
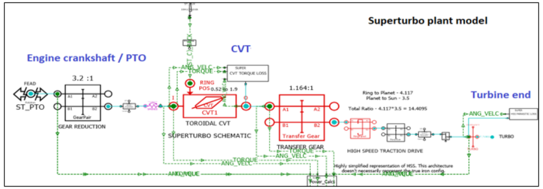
Technical Accomplishments & Progress

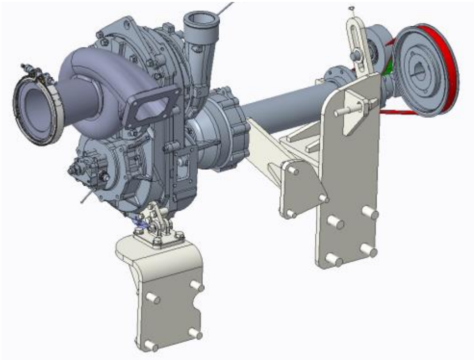
- Mechanical-Drive Turbo Accomplishments
  - Turbocompound performance simulated
    - Calibration optimization
  - Flow and sizing selection completed
  - Prototype turbine & housing completed
    - 5 nozzle rings for flow adjustment

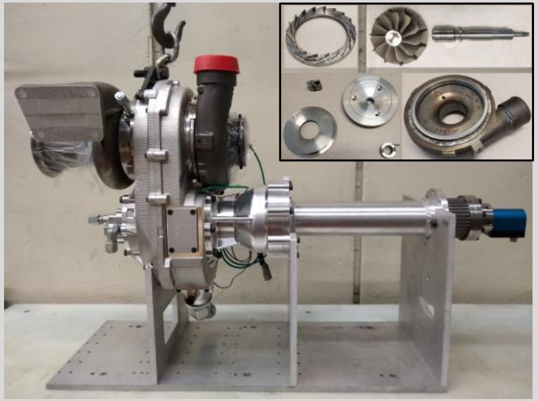


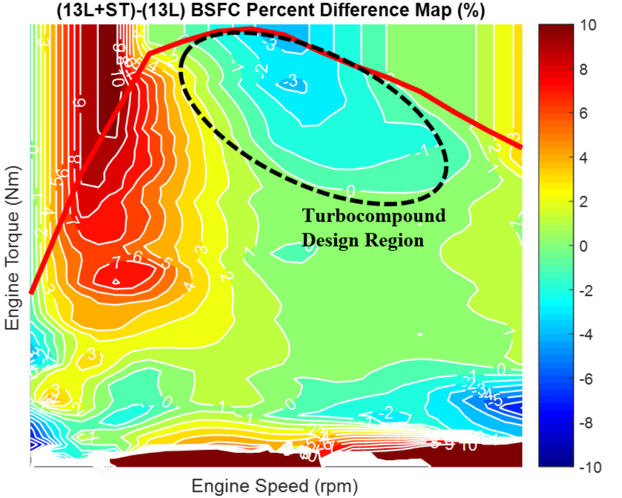




SuperTurbo Integration

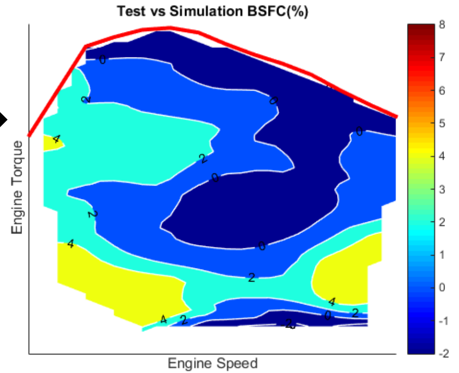




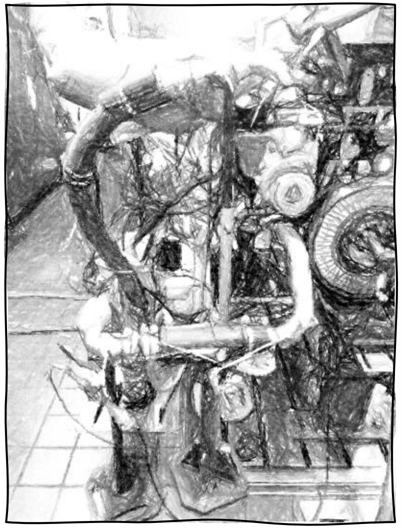


Technical Accomplishments & Progress

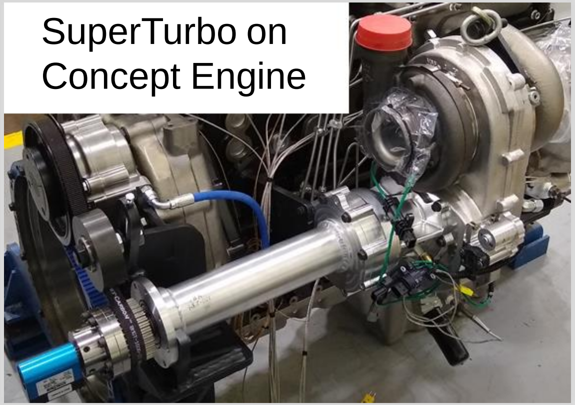
- Concept Engine and Aftertreatment
  - Test-to-Simulation (pre-hardware predictions) efficiency ranges confirmed
  - Phase 2 build and test cell installation complete
  - Validation testing underway



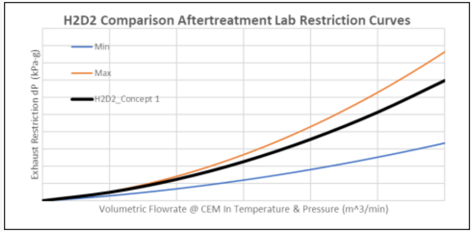
Engine System Installation in Test Cell



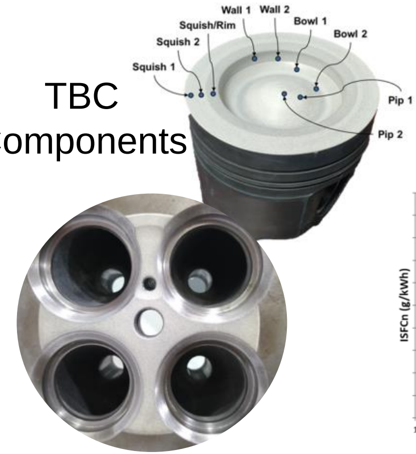
SuperTurbo on Concept Engine



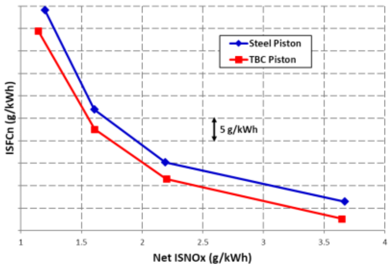
Aftertreatment Restriction



TBC Components



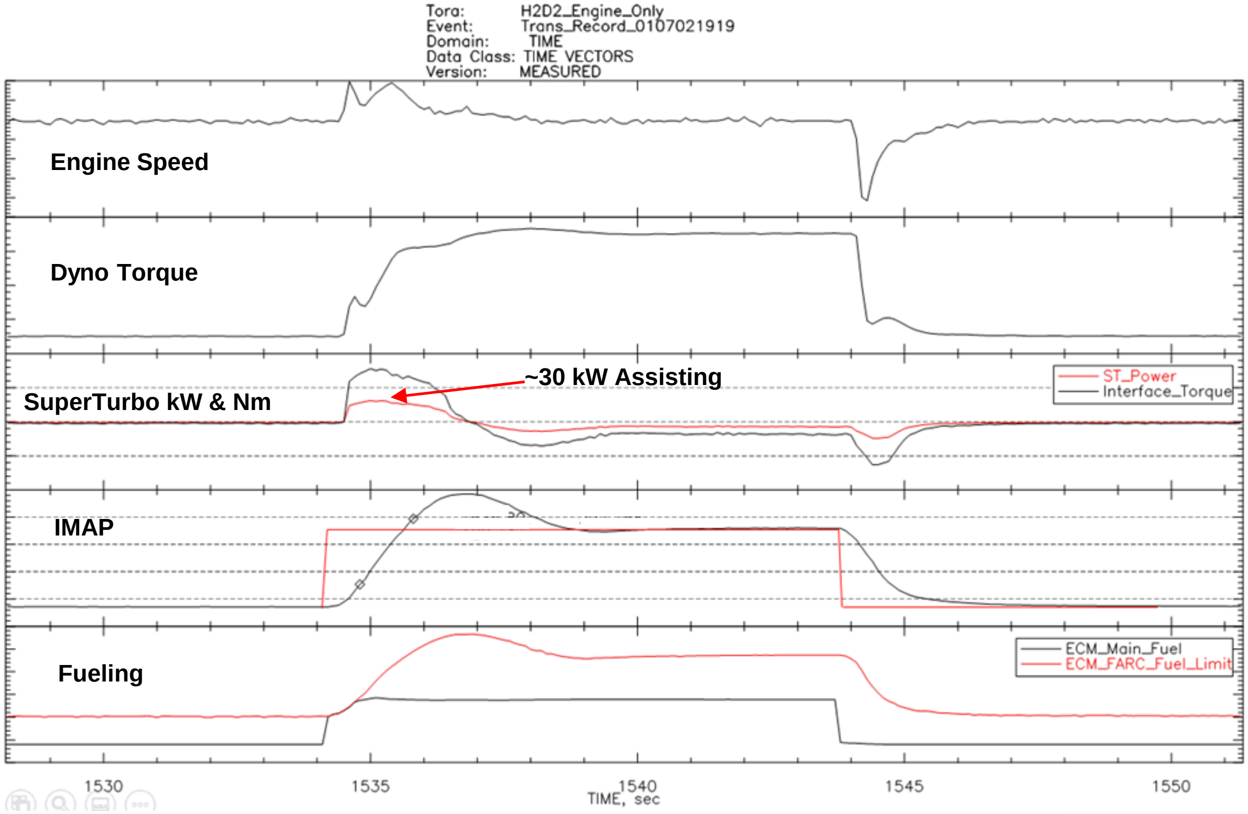
Single Cylinder Test



Technical Accomplishments & Progress

- Preliminary transient engine response and SuperTurbo tuning
- 1200rpm
- 20-80% Load

✓ Acceptable performance to begin validation testing campaign



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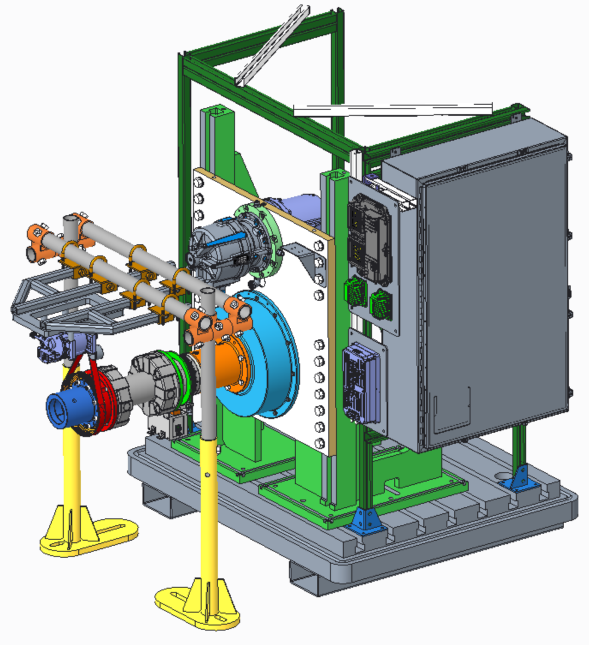
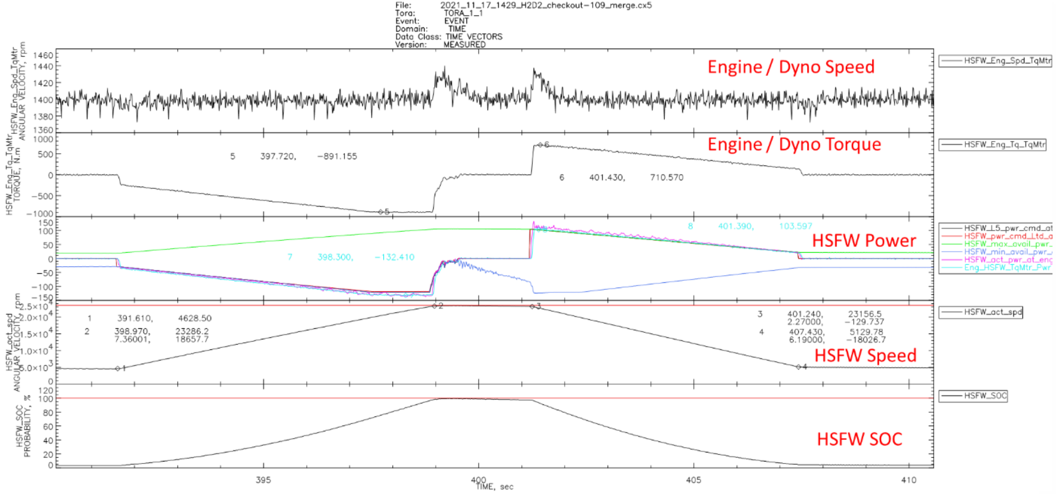
Technical Accomplishments & Progress

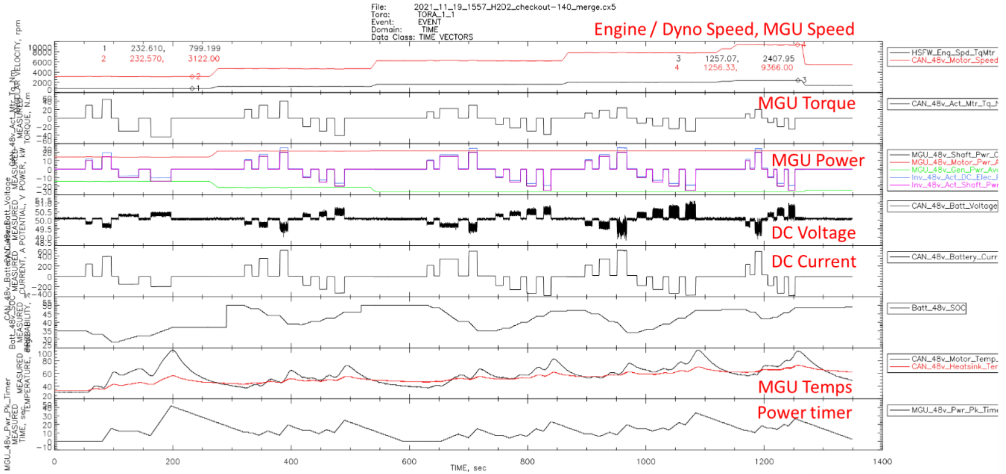
- High-Speed Flywheel (HSFW) and 48V Motor Generator Unit (MGU)
- “Hybrid-Only” system completed, and transient performance validated



Technical Accomplishments & Progress

- Hybrid device and driveline losses mapped
- HSFW & electric drive capability confirmed
  - +110kW discharging & -130kW charging power
  - +12,000 Nm/sec discharging @ engine input
- 48V MGU capability confirmed
  - +20 kW discharging & -25kW charging power
  - 1366 Nm/sec discharging @ engine input





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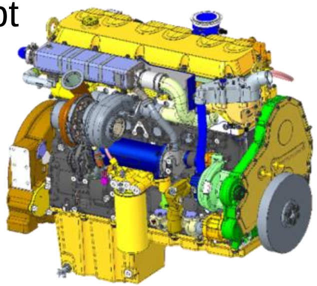
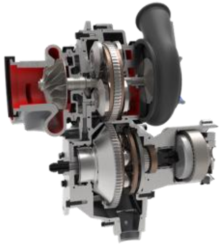
Technical Accomplishments & Progress

- Powersystem efficiency prediction range has been refined from year one and overlaps the program goal range of 17 (+/-) 2% - Project Quarter 13 Reporting

Concept Engine

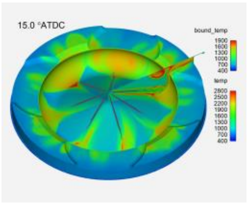


SuperTurbo



Flywheel

TBC



Transient Response Also Enables Engine Eff.

Current predictions of high-level efficiency contributions over the baseline 18L engine powersystem	
9.0-12.6%	13L Concept engine
0.3-1.1%	SuperTurbo Turbo-compounding
0.5-1.9%	High-Speed Flywheel (HSFW) & 48V MGU
0.5-2.0%	Thermal Barrier Coatings (TBC)
0.6-3.5%	Start/stop implementation
TBD	Advanced Engine Controls
2.0-3.0%	Reduced Cooling Parasitic
13.5-24.1%	***Current Total***

Response to Previous Year (2020 was the last) Reviewers' Comments

- "The approach is very good. The analysis, which led to the identification of how best to apply hybridization, was well done and resulted in identifying the approach that is being taken—hybridized front-end accessory drive (FEAD). It appears to be a very good example of analysis-led design."
  - Thank you for the positive feedback. This was our intent to let the analyses guide the design and research.
- "…some of the architecture selections, like the use of turbo-compounding as well as the use of both flywheel and motor generator unit, are puzzling since they introduce more complexity than is required."
  - We agree with the complexity challenges of the system. We view the main project purpose is to flush out where the real benefits are while demonstrating the maximum efficiency potential. A techno-economic analysis will be conducted to prioritize the most cost-effective aspects of the powersystem.
- "The reviewer also would have liked to see results from the thermo-fluid, structure, and dynamic simulations in order to address the air handling requirement in the power system. In the presentation, it is not clear how to increase the efficiency over start/stop implementation."
  - We added more detail in SAE paper 2021-01-0449. Start/stop is highly application dependent. Our efficiency increase comes from core engine & hybrid energy recovery. The air handling requirement comes from the application power levels and the transient response requirement to meet or exceed the 30% larger base engine.
- "The collaboration level seems to be adequate but requires more data exchange and feedback among the academic and industry partners. In particular, the work from the University of Texas at Austin is not well defined."
  - Yes, the definition of this work matured in the second phase of the project which was after this AMR in 2020. The University primarily focused on future HSFW bearing technologies and provided a report guiding future high-efficiency HSFW systems with industrial commercialization considerations.
- "With the analysis done and build-up underway, future work has been clearly identified. The team looks to be on track for their December Go/No-Go decision on proceeding with durability testing."
  - Thank you for this assessment and we did successfully pass the Go/No-Go #1 and #2 due to efficient and thorough analysis, design, and collaboration.
- "What application duty cycle is being selected for this architecture design? The PIs should consider whether the selected application duty cycle will create a challenge for a different application duty cycle."
  - The applications (wheel loader, articulated truck, excavator) had varying load, idle and braking histograms. These sufficiently represent some key off-road machines, and we believe that the approach to the modularity of the hybrid power system will allow different applications to be accommodated (i.e. less/more HSFW or +/- components).

Collaborations & Coordination

Prime & Sub-Recipients

- Caterpillar
- SuperTurbo Technologies
- University of Texas at Austin

Vendors

- Bosch
- Punch Flybrid
- Borg Warner

https://punchflybrid.com/

https://www.borgwarner.com/technologies/electric

https://www.boschautoparts.com/en/auto/diesel-parts

Remaining Challenges and Barriers

- Completion of the final validation testing is underway and on schedule, but lower priority items have been shifted later in the test plans to prioritize the full hybrid system testing. This is due to the high new content and complexity of testing the system.
- The validation testing of the Advanced Engine Controls impact on system efficiency has yet to be quantified and has been eliminated in favor of successful L5 hybrid controls efforts. This is due to resource constraints and hybrid-engine interaction complexity. Only simulation will be used to assess the Advanced Engine Controls.
- Final quantification and documentation of the predicted efficiency improvement ranges remains to be completed.

Proposed Future Research

- Finalize the engine-only and full-system hybrid validation testing
- Document steady-state and transient performance, emissions, and efficiency
- Complete the technoeconomic analysis leveraging the validation data
- Conclude the project with final reporting

				BP1							BP2				BP3			
				2018	2019				2020				2021				2022	
Item Title	**Item Description**	**Start Date**	**End Date**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**	**Q14**	**Q15**
Contracting, Project Kick-off, Project Management		**10/1/2018**	**6/30/2022**															
Concept Design and Simulation		**6/1/2019**	**3/31/2021**															
Decision Point 1	*IF 1D system level simulation validates that the target total fuel consumption reduction AND Tier IV Final emissions AND the power system can be packaged in to target off-road machines; THEN proceed to Task 3.*		6/30/2020							♦								
Major Subsystem Analysis & Specification		**3/1/2019**	**12/31/2020**															
Decision Point 2	*IF the structural, dynamics simulations show that the target 12,000 hour durability can be achieved AND the subsystems demonstrate required performance on bench tests; THEN proceed to ST-3.1*		12/31/2020									♦						
Hybrid Engine System Build & Integration		**4/1/2020**	**12/31/2021**															
Engine Integration & Assembly Complete			12/31/2021													♦		
Hybrid Engine System Validation		**9/30/2021**	**6/30/2022**															
Hybrid Engine System Performance Validation Complete			5/31/2022															♦
Technoeconomic Analysis and Documentation		**4/1/2022**	**6/30/2022**															
Documentation Complete			6/3/2022															♦

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Proposed Future Research

- Finalize the engine-only and full-system hybrid validation testing
  - The hybrid-only testing was completed and now the engine-only testing is in progress. The combined hybrid system will be brought together and tested.
- Document steady-state and transient performance, emissions, and efficiency
  - Steady-state engine and system performance will be mapped. Tailpipe emissions, efficiency, and heat rejection and typical durability measurements will be completed.
  - Transient operation includes machine work cycles, load response tests, and NRTC and RMC certification cycles for T4F emissions compliance.
- Complete the technoeconomic analysis leveraging the validation data
  - A total cost of ownership (TCO) analysis will be completed based on the bill of materials and the measured performance.
- A final report will be generated with all pertinent information

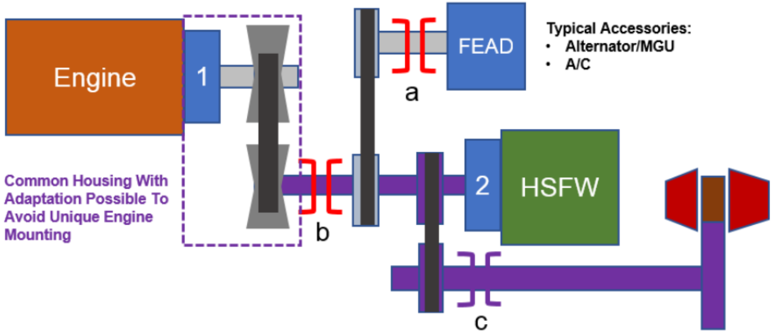
Program Summary

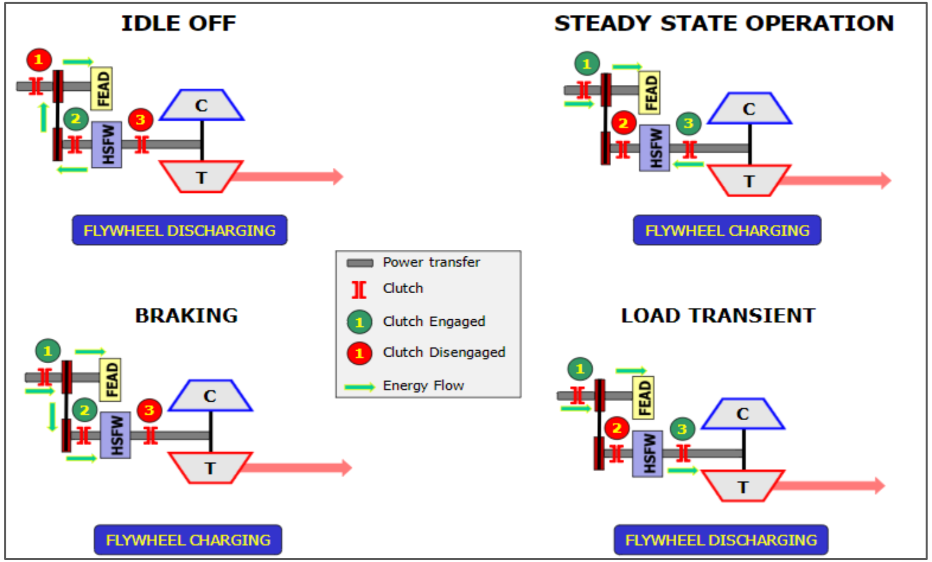
- Engine
  - The smaller concept engine was built and is on track to deliver the predicted efficiency improvements, and accounts for the majority of the system efficiency gains
  - Significant engine downsizing and efficiency improvements are partially enabled by the transient response assist capabilities of the hybrid devices
- Hybrid Aspects
  - The High-Speed Flywheel (HSFW) and Motor Generator Unit (MGU) performance was validated
  - The SuperTurbo was completed with successful integration and preliminary performance

- Caterpillar is reasonably confident in this system achieving off-road efficiency improvements of 17 (+/-2)%

Technical Backup (1)

Initial FEAD hybrid concept layout





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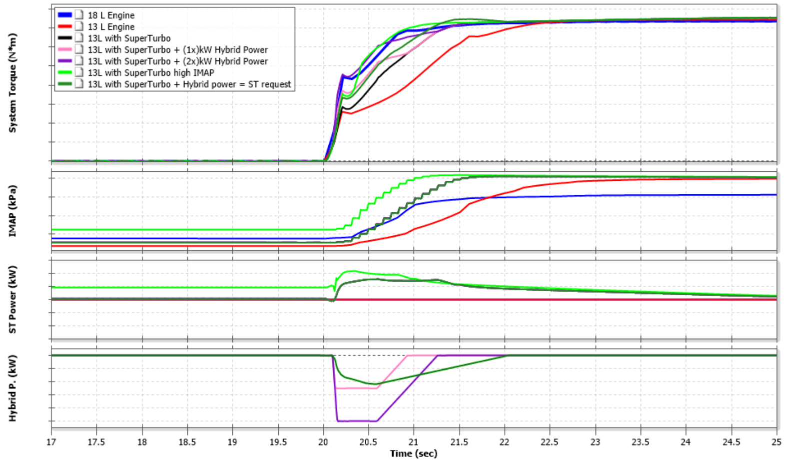
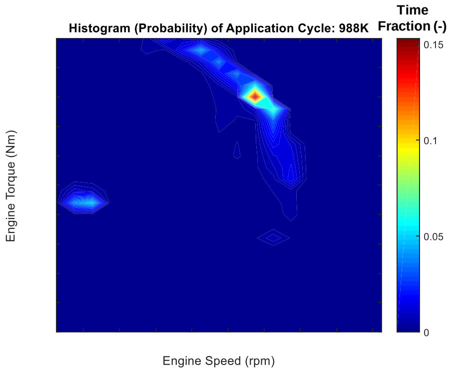
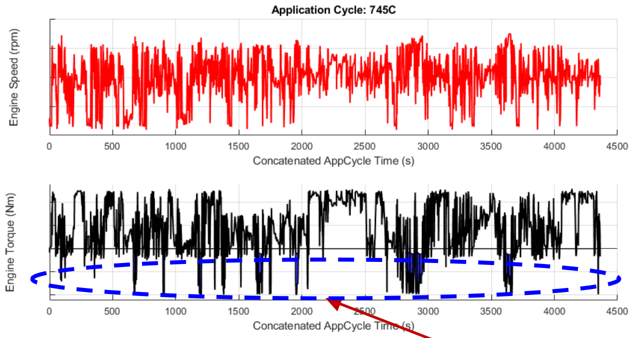
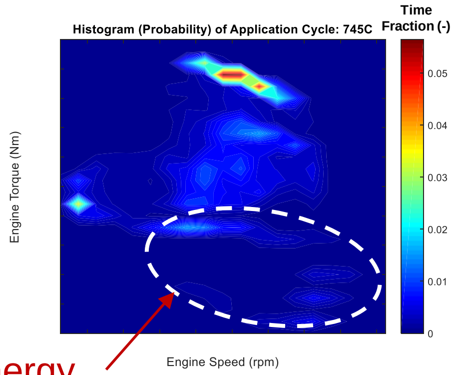
Technical Backup (2) – From 2020 AMR



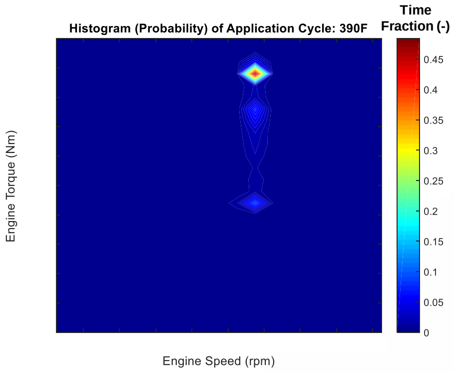
- Histograms, Application cycles, & energy recovery defined
- Transient load response critical focus on hybrid system definition







Recoverable Energy



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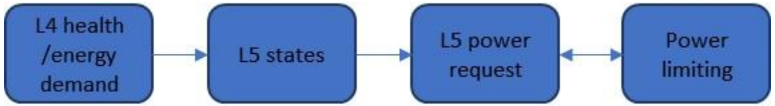
Technical Backup (3) – Hybrid Supervisory Controls

- Power System (L5) State Flow
- 4 Typical Operating States
  - Turbocompounding
  - Supercharging
  - Load/power acceleration
  - Engine Braking
- “r” is HSFW/MGU power split ratio
  - Dependent on L5 & L4 constraints
- PI/PID control implementation
- 16 parameter DoE’s run over the 19 transient cycles
  - HPC enabled, on the order of ~100 hours/iteration



	Eng_State	SuperTurbo_State	HSFW_State	MGU_State
Engine normal Run	1	-1	0	0
Engine normal Run	-1	1	0	0
Engine accel	0	1	-r	-1+r
Engine Braking	-1	0	r	1-r

Key Control Findings:
- **Fast, but not too fast energy recovery**
  - **Reduce overactive recovery/assist swings**
- **Bias HSFW SOC to upper range for superior acceleration assisting**